RESEARCH NOTE

Seismic-reflection constraints on lithospheric extension: pure versus simple shear

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1 INTRODUCTION

A number of different models have been proposed to describe the mechanism by which the continental lithosphere thins during extension. One end-member is the 'pure-shear' model (McKenzie 1978), in which extension occurs by a symmetric thinning of the crust and lithospheric mantle. The other is the 'simple-shear' model (Wernicke 1981), where the lithospheric mantle thinning is laterally offset from the crustal thinning by a detachment surface. There is general agreement that the pure-shear model as proposed by McKenzie, with its modifications for depth-dependent extension (Royden & Keen 1980; Rowley & Sahagian 1986; White & McKenzie 1988), finite rifting (Jarvis & McKenzie 1980) and lateral heat flow and flexure (Cochran 1981), is able to explain the width of the rift zone, the subsidence/uplift history and the free-air gravity edge effect anomaly that are observed at continental margins. Symmetric extension models fail, however, to predict all the features of continental margins. These include an asymmetry in the rift structures of some conjugate margins (Bally & Snelson 1980), the existence of outer 'basement' highs (Vierbuchen, George & Vail 1982) beneath the shelf break in slope and spatial variations in the proportion of syn-rift and post-rift sediments across rift-type basins (Steckler, Watts & Thorne 1988). These features are better explained (Lister, Etheridge & Symonds 1986) by the simple-shear model. The simple-shear model has therefore been quite widely applied to rift-type basins, even in continental margins such as the East Coast, USA (Bell, Karner & Steckler 1988) and Brazil (Ussami, Karner & Bott 1986), where there is little evidence in the published seismic-reflection-profile data for the existence of detachment faults. As a result, there has been intense debate in the literature on the relative contributions of pure shear and simple shear to the mechanism by which continents are thinned during extension.

Seismic-reflection-profile data (Klemperer & Hobbs 1991) have the potential to image detachment surfaces in the crust and therefore to distinguish between different models of extension. Detachment faults should be visible in these data if they are associated with a significant change in acoustic properties (such as reduction in porosity in the case of brittle faults or increased anisotropy in the case of ductile shear zones) or if they juxtapose rocks of sufficiently different acoustic impedance. Perhaps the best example of a detachment fault is the so-called 'S reflector' imaged in seismic-reflection profiles of the continental margin offshore France (De Charpal et al. 1978) and Iberia (Whitmarsh, Miles & Mauffret 1990). Although the original interpretation of this reflector by De Charpal et al. (1978) was in terms of a rheological boundary in an essentially pure-shear model, most workers (Le Pichon & Barbier 1987; Sibuet 1992; Hoffman & Reston 1992; Reston, Krawczyk & Klaeschen 1996) now attribute it to some form of detachment fault that during rifting separated the 'upper plate' (Lister, Etheridge & Symonds 1986) of one margin from the 'lower plate' of the other. Similar lower-crustal and upper-mantle detachment faults have also been described from BIRPS data over the North Sea (Gibbs 1983, 1984) and southwest of Cornwall (Dyment 1990) and from LITHOPROBE data across the Newfoundland continental margin (Tankard 1986).

Because of their general importance to understanding the mechanism by which continents rift, it is necessary to evaluate carefully the seismic-reflection data that have been used to image detachment surfaces, especially in basins where it is not possible to distinguish between the pure- and simple-shear models from their subsidence, thermal history or geometry of stratal onlap and offlap.

One such example is the Valencia Trough, an extensional basin of Neogene age in the western Mediterranean (Fig. 1). During 1988, the Lamont-Doherty Earth Observatory, the University of Paris-6 and the Institut Français du Pétrole carried out a two-ship multichannel seismic-reflection and -refraction study of the crustal and upper-mantle structure of the basin as part of project VALSIS. The seismic data were interpreted by Watts et al. (1990), Watts & Torné (1992), Torné et al. (1992) and Collier et al. (1994) as indicating that the northern margin of the Valencia Trough (i.e. the Catalan margin) is a rifted margin that formed by some form of pure shear. Torres, Bois & Burrus (1993), on the other hand, using the same data set, suggested that the Catalan margin had evolved by simple shear.

A component of the interpretation of Torres et al. (1993) was their identification on VALSIS Line 821, a multichannel seismic-reflection profile that crossed the Valencia Trough between Barcelona and Mallorca, of three packages of SE-dipping reflectors, which they suggest can be interpreted...
as 'shear planes' in the crust and upper mantle (Fig. 2b). Implicit in this suggestion is that these shear planes were part of a mid-crustal detachment system that, during the Late Oligocene and Early Miocene, linked extensional faults in the Catalan Coastal Ranges to offsets in the Moho beneath the Valencia Trough (Fig. 2a). We believe, however, that the dipping reflectors interpreted by Torres et al. (1993) as detachment faults are, in fact, multiples (Tucker & Yorston 1973) and hence are simply artefacts of the seismic-imaging technique that was used to acquire the data.

2 DATA PROCESSING AND ASSESSMENT OF THE MULTIPLE PROBLEM

The seismic-reflection profile under discussion was collected during cruise C2911 of R/V Robert D. Conrad using a 96-channel, 2.4 km long hydrophone streamer with a 10-gun, 5861 cu inch airgun (Watts et al. 1990). The data were processed at Lamont-Doherty to 11 s TWT. The processing sequence consisted of sorting into 25 m bins, velocity analysis, range-variable front mute, frequency–wavenumber velocity filtering, tail muting of near-offset traces for times greater than twice the sea-bottom arrival time, normal moveout, 48-fold stack, predictive deconvolution and bandpass filtering. Torres et al. (1993) stated that they only had a 5 s TWT migrated profile available at the time of their study and so they rely on the unmigrated stack for their interpretation of the deep structure. Several of the processing steps were aimed at suppressing multiples. Short-period multiples were suppressed by the application of post-stack predictive deconvolution, which used an operator with a length of 100 ms. Long-period multiples were tackled by a mild pre-stack f-k filter and the tail mute. However, it is our contention that significant long-period multiple energy remains in the stack.

McBride et al. (1994a) showed that the character of a multiple sequence in a seismic-reflection profile depends on the thickness of the sedimentary section and, more importantly, on the presence of high-amplitude coherent reflections from within the sediments. Stratigraphic interpretation based on a synthesis of all the available seismic-reflection-profile and well data (Maillard et al. 1992) suggests that line 821 comprises about 3 km of horizontal to gently dipping marine sediments of Neogene age. Within the Neogene there are several bright reflectors, the best known of which is an undulating reflector that corresponds to the Messinian unconformity. Conditions in the Valencia Trough are therefore conducive to strong multiple generation and so there is a good possibility that some of the deeper reflectors on this line are artefacts of the
imaging process. In addition to multiples generated by an individual shot, there has been some attention given in the literature recently to the problem of contamination of shot gathers by remnant multiples from previous shots, the so-called wrap-around multiple problem (McBride et al. 1994b). Fortunately, line 821 was shot with a long firing interval (30 s), so given the average water depths of 1000–2000 m this effect is not thought to be a problem in this particular data set.

In order to predict the long-period multiple sequence that would be expected to be generated from the imaged upper sequence, we have computed first, second and third autoconvolutions (McBride et al. 1994b) of the stacked reflection profile. This analysis is based on the assumption that the stacked data is a zero-offset section and accurately represents the reflectivity series of the sedimentary sequence. We generated our autoconvolutions from the same data as used by Torres et al. (1993) in their interpretation. As a further aid to the recognition of multiple energy we applied various constant-velocity, frequency–wavenumber (f-k) Stolt migrations to the stacked seismic section. Migrations are useful in our analysis as we expect near-surface generated multiples to migrate (or collapse) at lower migration velocities than real deep events. However, it is important to note that deep seismic-reflection data generally migrate with velocities of up to 50 per cent less than appropriate interval velocities derived from seismic-refraction data (Warner 1987). The reason for this is thought to be due to the low signal-to-noise ratio of deep reflection data, which produces discontinuous reflectors. Migrating at near-water velocity also collapses dipping multiple energy, enabling the true reflectivity to be more clearly seen.

We will demonstrate our contention that the SE-dipping reflections interpreted by Torres et al. (1993) as detachment faults are multiples for both of the interpreted sections presented in their paper. As a first example, we reproduce a section of line 821 from the centre of the basin in Fig. 2(d). In describing this figure, Torres et al. (1993) stated 'three packages of SE-dipping reflectors are also observed in the upper mantle (CDPs 1100–1800, 2100–2900 and 3200–5000), the latter one being the most prominent reflection set observed in the whole section'. CDPs 3200–5000 also produced the most prominent reflection set observed in the second autoconvolution of the whole line! We show this in Fig. 3(c), and the near-perfect correlation of the predicted multiples with the picks of Torres et al. (1993) is most compelling evidence. The SE-dipping reflectors within the crust are also well explained by predictions of the first autoconvolution (Fig. 3b). The overall SE dip is a consequence of the asymmetry of faulting in the basement (the short, steep northwest-dipping surfaces being less well imaged by the normal-incidence reflection technique). However, locally, where the basement structure dips gently NW, the reflectivity has a similar geometry, for example between CDPs 3200 and 3400, TWT 6 s. Again this is an indicator of their spurious origin. Our autoconvolutions also adequately match the dipping reflections in the mantle between CDPs 1100–1800 and 2100–2900, enabling us confidently to dismiss them also as multiples. As a further test of our findings, we used constant-offset migrations. For migration velocities above 2000 m s$^{-1}$ the dipping reflectors interpreted as primary events in the lower crust and mantle clearly overmigrate into concave 'smiles' (Fig. 3e). Even given a generous reduction of 50 per cent of the refraction-derived velocities for the lower crust and upper mantle, 2000 m s$^{-1}$ is an unrealistically low migration velocity, so we conclude that the events are water-column and near-surface multiples.

The interpreted section shown in Fig. 2(d) also shows a stippled area described by Torres et al. (1993) as 'abundant, subhorizontal, high-amplitude reflective zones'. We believe that this can be linked to a region about 1 s TWT thick that extends across most of the profile at traveltimes that correlate with water depth. Beneath the shallow water of the NNW margin, the reflective zone is seen between 4 and 6 s TWT, whilst here in the centre of the basin it deepens to 7–8 s TWT. The fact that the zone generally follows the bathymetric trend of the basin is characteristic of deep-water multiples. We believe that much of this reflectivity is also remnant multiple. The first autoconvolution shown in Fig. 3(b) confirms this to some extent, and although Torres et al. (1993) correctly identify some of the multiple events as 'diffractions', we believe that the strength of the basement multiple sequence must add to the apparent reflectivity.

The second example comes from the NW flank of the basin, where the water is comparatively shallow. Torres et al. (1993) describe the following in the text accompanying the section reproduced in Fig. 2(c): 'horizontal to SE-dipping reflection sets occur in the upper crust. It starts with many subhorizontal reflections located at the beginning of the profile (marked with stipple, CDPs 200–400). These reflections, though they are not very continuous, become SE dipping and penetrate into the lower crust towards the SE (marked with dots, CDPs 400–1000) and into the upper mantle'. In Fig. 2(a), these reflectors are interpreted as the main simple-shear plane linking extension in the Catalan–Vallencian domain with that in the centre of the trough. In Fig. 4 we show the second and third autoconvolutions of this part of the line, on which we have superimposed the upper-crustal reflective zones (outlined by dashes and labelled 1) and the lower-crustal/upper-mantle SE-dipping reflectors (dots). We believe that the coincidence of the picks of SE-dipping crustal and upper-mantle events of Torres et al. (1993) with prominent events in the second and third autoconvolutions, respectively, is compelling evidence that they are multiples (Figs 4b and c). Again the overall SE dip is a consequence of the asymmetry of faulting in the basement. However, the upper-crustal reflective zone (labelled 1) to which Torres et al. (1993) suggest the deeper reflectors are linked is not so easily explained by our autoconvolutions, so it may be genuine. However, their coherency is not significantly enhanced following migration, and even at a migration velocity of just 1550 m s$^{-1}$ they may overmigrate (Fig. 4d), so their existence is not certain. The reflectivity in the lower crust (labelled 3) in this section is not explained by the multiple prediction, and at least between CDPs 200 and 800 is enhanced by migration—and we believe that this is also real. However, the reflective zone between CDPs 1200 and 1400 and 5 and 6 s (labelled 2) TWT, which is part of the basin-wide region, is so close to reflectivity predicted by the second autoconvolution that it must at least partly explain this zone.

Independent evidence that the lower-crustal/upper-mantle SE-dipping reflectors are artefacts comes from two other seismic profiles collected in the area. The first profile is two-ship wide-aperture data that were acquired at the same time as the single-ship CDP profile on which Torres et al. (1993) based their interpretation. These two-ship data have a much wider total offset (0–5.4 km) than the single-ship CDP (0–2.4 km) and therefore have higher differential moveout from...
Figure 2. (a) Interpreted cross-section of line 821 according to Torres, Bois & Burrrus (1993). 1 = water; 2 = EBRO group (Pliocene-Quaternary); 3 = Messinian; 4 = Castellon Group (Serevallian- Tortonian); 5 = lower Neogene (Aquitanian-Langhian); 6 = volcanics; 7 = main geodynamic features of their interpretation. (b) Line drawing of VALSIS Line 821 according to Torres, Bois & Burrrus (1993). Same legend for Tertiary infill as in (a). Solid circles mark the refraction Moho based on Torre et al. (1992) and Gallart et al. (1990). The shaded areas in the crust and upper mantle indicate areas that Torres, Bois & Burrrus (1993) suggest have 'numerous subhorizontal high-amplitude reflections'. The line drawing is based on data shown in (c) and (d). (c) Example of data (CDPs 200-1500). EG = Ebro Group; CG = Castellon Group; LN = lower Neogene; B = basement; D = diffractions; M = refraction Moho. The shaded areas in the crust and upper mantle are as in (b), except they have been outlined by thick dashed lines. Heavy black dots mark distinct SE-dipping reflections. (d) Example of data (CDPs 3700-5400). MR = multiple reflection. All figures reprinted from Torres et al. (1993) with kind permission of Elsevier Science-NL.
Seismic-reflection constraints

Figure 2. (Continued.)

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(a) Valsis 821 Unmigrated stack

(b) Valsis 821 1st autoconvolution
Figure 3. (a) Unmigrated stack. The data is identical to that shown in Fig. 2(d) but it is reproduced here with identical plotting parameters, as are the following illustrations. The interpretation of the crustal features by Torres et al. (1993) shown in Fig. 2(d) is plotted for reference. (b) First autoconvolution (primary series*primary series, where the primary series is the observed sediment reflections) of the stacked data shown in (a) windowed between the seabed primary and 0.5 s TWT below the top of basement. Assuming that the primary sedimentary section gives an estimate of the true reflectivity series, the first autoconvolution predicts the general form of the first multiple series. Reflections that are explained by this autoconvolution are marked with black dots, the others are shown with white dots. (c) Second successive autoconvolution (primary series*primary series*primary series) of the stacked data. This predicts the general form of the second multiple series. Reflections that are explained by this autoconvolution are marked with black dots, the others are shown with white dots. (d) Frequency–wavenumber migration with a constant velocity of 1550 m s⁻¹. (e) Frequency–wavenumber migration with a constant velocity of 2200 m s⁻¹. For migration velocities any higher than this, the SE-dipping reflectors below 6 s TWT clearly overmigrate into concave ‘smiles’. Such a low-threshold migration velocity is characteristic of the near-surface multiples.
which to discriminate between multiples and primary events by stacking (Collier et al. 1994). The second profile was collected as part of the STREAMERS/ESCI project and approximately parallels VALSIS 821 but is about 50 km to the west. This profile was collected with superior equipment for imaging deep structure, namely a 180 channel, 4.5 km streamer and 7118 cu inch airgun array (Vidal et al. 1995). Neither of these profiles show any evidence for any SE-dipping reflectors in the lower crust or upper mantle.

3 IMPLICATIONS

These considerations of seismic-reflection-profile data from the Valencia Trough have a number of implications for the interpretation of seismic-reflection-profile data from other rift-type basins. First, the processing of seismic-reflection data places much emphasis on multiple suppression and therefore many interpreters believe that it has been completely successful. Our experience, however, suggests that more thought should be given to multiple identification schemes before interpretation of the stacked sections proceeds. It is also, we believe, better to interpret a seismic-reflection profile that has had a moderate multiple-suppression processing applied (having correctly identified remnant multiples) than one that has been harshly processed, since there is a risk that primary reflectors may have been distorted or even removed. The problem of multiple recognition in deep-water seismic-reflection-profile surveys has also been investigated by Hardy, Warner & Hobbs (1989) and Hardy & Hobbs (1991). In addition to the tests suggested here they recommend performing stacks of the data at multiple velocities.

In summary, we believe that the SE-dipping reflectors, interpreted by Torres et al. (1993) as detachment faults, are artefacts of the seismic-imaging technique used to collect the data. The seismic data across the northern margin of the Valencia Trough is consistent, we believe, with a model in which continental thinning occurs by pure shear and does not require a simple-shear model in order to explain it. Indeed, Watts & Torné (1992) have shown that a pure-shear model when modified for the effects of finite rifting (Cochran 1981) is able to explain the tectonic subsidence/uplift history of the margin as revealed in commercial well data. Thus, we believe Torres et al. (1993) have overstated the role of simple shear in controlling the mechanism by which continental extension

Figure 3. (Continued.)

| Figure 4. (a) Unmigrated stack. The data is identical to that shown in Fig. 2(c) but it is reproduced here with identical plotting parameters in the following illustrations. The interpretation of the crustal features by Torres et al. (1993) shown in Fig. 2(c) is plotted for reference. (b) Second autoconvolution. Reflections that are explained by this autoconvolution are marked with black dots, the others are shown with white dots. (c) Third successive autoconvolution. Reflections that are explained by this autoconvolution are marked with black dots, the others are shown with white dots. (d) Frequency–wavenumber migration with a constant velocity of 1550 m s\(^{-1}\). (e) Frequency–wavenumber migration with a constant velocity of 2200 m s\(^{-1}\). |
Figure 4. (Continued.)
occurred during the Late Oligocene and Early Miocene in the Valencia Trough region. A similar situation appears to have occurred in the North Sea basin where Klemperer & White (1989), for example, have pointed out that despite the interpretations of Gibbs (1983, 1984) no seismic-reflection profile over this basin has actually imaged a low-angle detachment that extends through the whole crust and across the Moho. Indeed, earlier work by one of the authors (Burrus, personal communication) indicates problems with the application of the simple-shear model to other basins in the western Mediterranean (e.g. Gulf of Lyon).

The problem may be even more acute at the so-called 'Atlantic-type' continental margins, where despite the acquisition of large numbers of high-quality seismic-reflection profiles, there is little evidence for large-scale detachment faults. Unfortunately, few of these profiles are conjugate and so it has not been possible to discriminate between the pure- and simple-shear models. However, the best example to date is probably the Newfoundland/UK conjugate margin (e.g. Keen et al. 1989). A striking feature of this margin is the symmetry of the deep structure of the rift zone. A second example is the Labrador/Greenland conjugate margin (Chian, Louden & Reid 1995). Although this margin shows an element of asymmetry in the Moho geometry, Chian et al. (1995) appealed to a pure-shear model with a slow rate of extension (Bassi, Keen & Potter 1993) to explain the symmetry of the crustal velocities. The best evidence for detachment faults appears to be the 'S reflector' imaged off Iberia. However, even here there is controversy (Reston, Krawczyk & Klaeschen 1996) concerning its continuation into the unstretched continental crust to the east and oceanic crust to the west. The main problem is the lack of a suitable multichannel seismic profile on the conjugate (i.e. Flemish Cap) margin. The relative role of pure and simple shear in controlling the mechanism of crustal thinning at this margin is therefore also unclear. Future seismic-reflection studies of these margins using airgun sources and streamers that are designed so as to avoid problems with seafloor and subseafloor multiples, together with improvements in multiple suppression and recognition techniques, offer the most promise, we believe, of addressing this problem in the future.

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